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(71) Applicant (for all designated States except US): AMERSHAM INTERNATIONAL PLC [GB/GB]; Amersham Place, Little Chalfont, Buckinghamshire HP7 9NA (GB). (72) Inventors; and (75) Inventors/Applicants (for US only) : GARLAND, Peter, Bryan [GB/GB]; Hope Cottage, Sunnyway, Old Bosham, West Sussex PO18 8H0 (GB). HEANEY, Paul, James [GB/GB]; 37 The Lawns, Hatch End, Pinner, Middlesex HA5 4BL (GB). POLLARD-KNIGHT, Denise, Vera [GB/GB]; 4 Drury Road, Harrow, Middlesex HA1 4BY (GB).		Published With international search report.	
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(57) Abstract A method of sequencing a single-stranded nucleic acid chain involves providing an immobilised complex of a template to be sequenced and a primer. This complex is exposed to flow containing only one dNTP at a time. The primer is extended only if the dNTP is complementary to and can hybridise to the next free nucleotide of the template. Each such polymerisation event is detected, preferably directly and by spectroscopic means. Preferred detection techniques include fluorescence detection and absorption spectroscopy (non-evanescent wave) and particularly evanescent spectroscopy e.g. surface plasmon resonance spectroscopy.			

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SEQUENCING METHOD

5 Introduction

Determination of the sequence of nucleotide bases in 2'-deoxyribonucleic acid (DNA) and to a lesser extent ribonucleic acid (RNA) is a central technology for much of present day molecular biology and its many applications. There are currently two main methods available for sequencing DNA, and both involve using a DNA polymerase enzyme to make a copy of a suitably primed strand of the unknown DNA which acts as a template. In the so-called chain-termination method of Sanger et al (1977), the growing copy strand is randomly (at least, randomness is intended) terminated by incorporation of a 2', 3'-dideoxyribonucleotide (ddNTP) competing with the normal 2'-deoxyribonucleotide (dNTP) for addition to the 3'-end of the growing copy strand. By using suitable conditions and four separate preparations corresponding to dATP with ddATP, dCTP with ddCTP, dGTP with ddGTP and dTTP with ddTTP, all possible lengths of terminated copy strands are available. They are separated by size by gel electrophoresis, and detected by means of an incorporated label, commonly radioactive but more recently fluorescent (Smith *et al*, 1986; Ansorge *et al*, 1987). The DNA sequence of the copy, and therefore the complementary sequence of the template, is derived from the pattern of chain lengths detected for the separate A, C, G and T termination mixture.

The chemical degradation method of Maxam and Gilbert (1977) also uses DNA polymerase catalysed formation of a template-copy. The dNTP's are radioactive with ^{32}P (or ^{35}S) at the α -position, so the copy is also radioactive. Chemical treatments specific for

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different bases cleave the copy into sets of fragments which, as with the Sanger dideoxy chain termination method, can be separated by gel electrophoresis and detected (by autoradiography) to yield patterns from 5 which the DNA sequence can be deduced. Variants of these methods have been described (Church & Kieffer-Higgins, 1988; Gish and Eckstein, 1988), but are still dependent upon gel electrophoresis to separate DNA fragments, and upon such methods such as radiolabelling 10 for detection of the separated fragments.

All of these methods are slow, complex and expensive in relation to the needs for DNA sequencing. For example, the best rates of DNA sequencing to date are about 600 nucleotides in 12 hours, using an 15 automated instrument (Landegran et al, 1988). This corresponds to 50 bases per hour or 0.014 bases per sec. This rate is approximately two-orders of magnitude lower than that thought necessary for large-scale sequencing in the Human Genome Project (Alberts 20 et al, 1988).

Three laboratories have reported attempts to avoid the needs for copy-strand fragments and their length-determination by gel electrophoresis. Hyman (1988) immobilised the DNA template primer with 25 polymerase on an ion-exchange material and exposed the complex to a flow wherein only one of the four dNTP's was present at a time. A downstream detection system then detected the pyrophosphate liberated in the DNA polymerase reaction:-
30 template - primer + dNTP → template - (primer + dNMP) + PP_i where dNMP stands for the added nucleotide residue, PP_i for pyrophosphate. The sequencing rate was approximately 1 base every 10 minutes. Melamede (1987) also proposed the use of an immobilised DNA 35 template, primer and polymerase complex exposed to a flow containing only one species of dNTP at a time.

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However, incorporation of dNTP into the copy was calculated not from measurements of pyrophosphate release but from the difference in dNTP concentrations entering and leaving the flow cell which contains the 5 complex of DNA template and polymerase. No experimental data were presented.

Jett (1989) provided a single stranded DNA or RNA sequence of labelled nucleotides, complementary to the sequence to be determined, suspended in a moving 10 flow stream. An exonuclease sequentially cleaved individual basis from the end of the suspended sequence. The resulting train of individual labelled nucleotides was passed to a downstream location for analysis of the individual nucleotides.

15 This invention

As with the methods of Melamede (1987) and Hyman (1988), we also use an immobilised complex of template and primer, exposed to a flow containing only one dNTP at a time. We differ however in that we 20 directly measure the growth of the template copy, rather than infer it indirectly from changes in the composition of the flow medium. The methods of detection are preferably spectroscopic and do not require the further addition of chemical reagents to 25 effect measurement of template-copy growth. The spectroscopic methods are:-

- i) Evanescent wave spectroscopy
- ii) Fluorescence detection (non-evanescent wave)
- iii) Absorption spectroscopy (non-evanescent wave)

30 Alternatively the individual nucleotides may be labelled, e.g. radioactively. Attachment of each successive labelled nucleotide to the immobilised complex is then detected by an increase in total radioactivity.

35 Irrespective of which detection method is used, the time-dependent signal arising from

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polymerase catalysed template copy growth depends on the availability of the correct (i.e. complementary) nucleotide for base-pairing with the template at the growing point of the copy. If all four nucleotides

5 are absent, there is no polymerase activity. If only one nucleotide is present, then extension of the copy will occur only as far as base-pairing with the template is possible in the absence of the other three nucleotides.

- 10 Preferably a continuous flow of pulses of deoxynucleotides (dATP, dCTP, dGTP, dTTP) or ribonucleotides (ATP, CTP, GTP, UTP) or analogues of these nucleotides, each separated by a wash pulse, is passed over the tethered template DNA or RNA (with any
15 extension and linkers, and the primer oligonucleotide). This is done under conditions, e.g. in the presence of a suitable polymerase enzyme, to cause an extension of the primer by addition of the nucleotide (or analogue) to the 3'-end of the primer if the nucleotide (or
20 analogue) is complementary to and can hybridize with the next free nucleotide of the template (going from the 3'-end towards the 5'-end). Conditions of solvent, temperatures, ionic strength and concentrations of any polymerase enzyme activating cations and anions are
25 maintained such that the polymerase is enzymatically active in the presence of its substrates. Because only one of the four nucleotides is present at a time, extension of the copy strand occurs in jumps depending on whether the appropriate nucleotide for pairing with
30 the next unpaired base of the template strand is present or not. Each such jump is herein designated a polymerisation event. Thus the signal also exhibits time-dependent jumps that reflect the extension jumps (polymerisation events) of the copy strand.
35 Furthermore, the size of the signal jumps is proportional to the number of bases added in each

- 5 -

extension jump (i.e. proportional to the number of polymerisation events), e.g. the addition of say three adenine residues gives three times the signal given by the addition of only one such residue. Because the
5 copy strand can be extended by only an integral number of bases (0, 1, 2, 3...) during any extension jump, then the optical signals are quantised. This property of the signals is highly advantageous for calibration and for discrimination against noise.

10 For simplicity, this invention is hereafter described in terms of DNA sequencing, using a DNA template with DNA polymerase and deoxynucleotides (dNTP's) or analogues to make a DNA copy. It should be noted that RNA technologies could be used : e.g. (i)
15 DNA as the template, RNA polymerase to make an RNA copy (ii) RNA as the template, reverse transcriptase to make a DNA copy, and (iii) RNA as the template, RNA replicase to make an RNA copy.

(i) Evanescent wave spectroscopy (EWS)

20 Evanescent wave spectroscopy is defined in the present context as embracing three related methods: (i) attenuated total reflection (ATR) spectroscopy (ii) total internal reflectance fluorescence (TIRF) spectroscopy, and (iii) surface plasmon resonance (SPR) spectroscopy. Each of these three spectroscopic techniques examines an optical property of a solution bordering a surface where total internal reflection of a light beam has occurred. In each case the incident and reflected beams are on the side of the surface
25 distal to (i.e. remote from) the solution under study, whereas the evanescent wave is established on the solution side of the surface but extends into that solution for a very short distance, typically less than the wavelength of the incident/reflected beam.
30 Spectroscopy by ATR or TIRF requires only a transparent material such as glass or quartz to create the
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interfacial surface with the solution, whereas SPR spectroscopy requires that the glass or quartz surface be coated with a thin (e.g. 50nm) metal layer of, for example, silver. All three methods can detect the
5 exchange of solute molecules between the bulk phase of the solution and the interfacial surface, albeit by different means. ATR spectroscopy detects the absorption of evanescent wave light by molecules, with appropriate absorption spectra, that lie within the
10 evanescent wave region. If the absorbed light is re-emitted as fluorescence then the emission can be measured with a suitable detector, such as a photomultiplier tube, leading to TIRF spectroscopy. Thus both ATR and TIRF spectroscopy measure the absorption
15 of light by molecules at or close to the interfacial surface, the difference being that ATR measures the absorption directly whereas TIRF measures it indirectly, as re-emitted fluorescence. By contrast, SPR spectroscopy measures changes of refractive index
20 that may occur in the SPR evanescent wave region, but, just as with ATR and TIRF, those changes arise due to redistribution of molecules between the bulk phase of the solution and the evanescent wave region. For a review of these methods, see Sutherland and Dahne,
25 1987.

Having given a brief outline of evanescent wave spectroscopies, we can describe their application to DNA sequencing. The DNA molecule of unknown sequence, derived from biological techniques such as
30 DNA cloning or polymerase chain reactions must (i) be single stranded (ii) be attached either directly or indirectly by either its 3' or 5' end to the interfacial surface of an EWS device, and (iii) possess a known sequence, either naturally occurring or added,
35 at its 3' end such that a complementary oligonucleotide (primer) can be hybridised to create a run of double

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stranded DNA. Thus in the presence of DNA polymerase and deoxyribonucleotide triphosphates (dNTP) the unknown DNA acts as a template for the synthesis of a complementary copy extending by growth from the 3' end 5 of the primer. DNA polymerase catalysed growth of the template copy results in recruitment of dNTP's from the bulk phase to the interfacial region where the template is tethered. It is assumed that the copy strand remains base-paired to the template strand, and does 10 not diffuse away. Template copy growth can therefore be measured by EWS spectroscopy. ATR spectroscopy requires that the incident beam be in the wavelength region of a major absorption band of the dNTP's, typically about 260nm. TIRF spectroscopy requires that 15 the nucleosides incorporated into the template copy can be excited to fluoresce by the evanescent wave : fluorescent DNTP analogues are required. SPR spectroscopy has fewer limitations : dNTP analogues are not required (although substitution with refractive 20 index enhancing atoms such as Br, I or Hg might be advantageous for sensitivity) and the choice of wavelength is not critical.

Figure 1 illustrates the experimental set up, shown for the specific case of SPR spectroscopy. The 25 3' end of the template DNA (or its extension) is attached to the interfacial silver surface, and the primer oligonucleotide is hybridised to the template. Alternatively the primer could be attached to the surface and the template DNA hybridised to the primer. 30 Clearly the polarity of attachment can be reversed:- the 5' end of the template bound to the surface, and the primer hybridised to the free 3' end of the template or extension.

Figure 2 shows idealised experimental results 35 using SPR spectroscopy. The sequence of the template being copied is read directly from the associations

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between jumps in the EWS signal and the particular dNTP pulse present at the template site.

(ii) Fluorescence detection

Because each cycle of dNTP (or rather its fluorescent analogue) is preceded and followed by a wash, EWS (TIRF) is not mandatory to distinguish the fluorescence signal arising from the template-copy from free nucleotides in the medium. Thus a more conventional optical geometry can be used, and immobilisation of the template-primer-polymerase complex can be on beads, fibres or membranes rather than an evanescent wave surface.

A serious drawback of the fluorescent method for DNA sequencing, irrespective of whether or not it uses an evanescent wave, is the fact that the absolute size of the signal grows as the copy strand grows. This makes it harder to detect the increments (jumps) of fluorescence resulting from strand extension.

Even under ideal conditions (Poissonian photon-counting statistics, zero background and noise-less excitation source), it is necessary to increase the measurement time for each increment of nucleotide addition in proportion to the number of such increments in order to maintain constant sensitivity for the detection of each successive fluorescence increment. For example, if it took 1 sec to measure the fluorescence of the first added nucleotide to a satisfactory accuracy, then 10 seconds would be needed to measure the tenth added nucleotide, 100 seconds for the hundredth, and so on. Thus what is intended to be a fast DNA sequencing method becomes progressively slower as it proceeds.

There are two instrumental solutions to this problem. The first is to increase not the duration of measurement for successive increments of fluorescence, but the excitation intensity. By this means the

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accumulation of photon counts required for accuracy can be achieved in a constant time. Technically this can be arranged with a CW laser excitation source equipped with an acousto-optic or electro-optic modulator to
5 modify the beam intensity transmitted to the sample. The second solution is to irreversibly photobleach the sample fluorescence with an intense light pulse at periodic intervals, thereby resetting the sample fluorescence to zero before it can significantly
10 degrade the detection of successive increments. Technically this can also be achieved with a CW laser equipped with a modulator (Garland, 1981).

The fluorescent probe itself can be attached to each of the four dNTP's. As each dNTP is presented
15 separately to the template-primer-polymerase complex, the same fluorophoric group can be used for each dNTP. Alternatively, fluorescent dideoxy chain terminators can be used in competition with unlabelled dNTP's, under conditions where the number of terminated chains
20 is not so large as to deplete the number of unterminated chains to the point where fluorescence increments associated with chain termination become difficult to detect. Each dNTP is presented with its corresponding fluorescently-labelled ddNTP to the
25 template-primer-polymerase complex, and a single fluorophore is sufficient.

(iii) Absorption spectroscopy

The direct measurement of template copy growth by detecting the increase in ultraviolet light
30 absorption at approximately 250-260nm caused by addition of new nucleotides to the copy strand is not sensitive. However, the availability of relatively large amounts of starting material (template) through DNA cloning or polymerase chain methods, allied to
35 powerful U-V laser sources such as frequency-tripled Nd-Yag lasers, makes it technically possible to measure

- 10 -

template-copy growth directly by absorption spectroscopy.

The advantages of these optical methods over existing methods are very large. They include:-

- 5 - potential for high speed (e.g. 10 bases/sec)
- miniaturisation and parallel flow lanes
- no need for gel electrophoresis
- direct signal transfer to computer
- no need for radioactive nucleotides
- 10 - greater chance for complete automation due to absence of gel separation steps.

The following Examples illustrate the invention.

15 EXAMPLE 1

Detection of Polymerase Catalysed Nucleotide Addition on a Silver Slide using Surface Plasmon Resonance

Materials and Methods

20 Reagents

1. 0.25pmole/ μ l solutions of hybrid DNA (consisting of a 17 nucleotide primer sequence hybridised to a 20, 27 or a 97 nucleotide template sequence) prepared in 10 mM phosphate buffer pH 7.4 containing 10mM phosphate
- 25 buffer pH 7.4 containing 10mM MgCl₂ and 50mM NaCl.
2. 10mM phosphate buffer pH 7.4 containing 10mM MgCl₂ and 50mM NaCl (sequencing phosphate).
3. 10mM phosphate buffer pH 7.4.
4. DNA Polymerase I "Klenow fragment" diluted in sequencing phosphate containing 250 μ M dATP, dCTP, dGTP and dTTP.
- 30 5. Block solution of 0.05% BSA in sequencing phosphate.

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Equipment

Rig

A single beam direct reference rig using a
5 632.8nm wavelength helium neon laser which interrogated
two spots and subtracted one signal from the other, was
used.

Pump and flow cell

A modified step motor pump which held 2
10 syringes was used to deliver different or identical
solutions to the 2 segregated areas of the flow cell.

Silver Slides

Silver coating thickness on the slides was
greater than that normally used for SPR work i.e. 60nm
15 to achieve an SPR width of approximately 0.6 degrees at
approximately 5% from the reflectance minimum.

Slide Tolerance Limits

The slides were rejected if the SPR profiles
20 on both areas of the silver slide were not similar in
shape and minimum.

Experimental Procedure

1. 1ml 10mM phosphate buffer ph 7.4 was added at
25 4 μ l/second to the silver slide.
2. 1ml sequencing phosphate was added at 4 μ l/second.
3. 1ml of hybrid (17/20 was used as the reference DNA)
17/27 or 17/97 was added at 2 μ l/second followed by 3
washes in sequencing phosphate.
- 30 4. 1ml of BSA block solution was added at 2 μ l/second
followed by 3 x 0.3ml washes in sequencing phosphate.
5. 1ml of Klenow plus nucleotides was added at
2 μ l/second followed by 3 x 0.3ml washes in sequencing
phosphate.

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Angle and time scans were obtained at strategic points during the experiment. The overall shift difference caused by the addition of extra nucleotides (3 for the reference, 10 for the 17/27 and 5 80 for the 17/97) was recorded.

Results

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Hybrid	Hybrid coverage moles/mm ²	Nucleotide added moles/mm ²	SPR shift % reflectivity
17/97	3×10^{-15}	2.3×10^{-13}	3
17/27	Not determined	Not determined	2

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The figures in the last column are additional changes over and above those of the 17/20 reference.

Conclusion

20

The SPR signal obtained from the addition of ten nucleotides to a primer-template complex by the Klenow fragment of DNA polymerase could be measured above the signal obtained from a three nucleotide 30 addition in the reference sample. This clearly demonstrates the detection by SPR of the addition of seven nucleotides.

If the following change is made to the equipment then single nucleotide addition will be 35 detected by SPRS.

The experiments were conducted by recording

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one reflectivity measurement per second. This gives signal to noise resolution down to seven nucleotides. However by increasing the measurement rate to 1000 per second an improvement by a factor of 30 can be achieved
5 which will permit detection of single nucleotide addition. Noise is proportional to the square root of the number of readings taken, therefore the square root of 1000 equals 30.

10 EXAMPLE 2

Polymerase Catalysed Single Nucleotide Addition to template DNA Immobilised on Silver Slides

Method

- 15 1. Template-primer DNA (a 17 nucleotide primer annealed to a 97 nucleotide template) was immobilised on the silver slides at a coverage of 1.25×10^{-13} moles/silver slide.
- 20 2. The 4 nucleotide / polymerase mixes were made up as follows in 10mM phosphate buffer pH 7.4 containing 10mM MgCl₂ and 50mM NaCl:-
- a) 5μM deoxyadenosine 5'-triphosphate + 200U/ml Klenow fragment (Amersham T2141Z),
- b) 5μM deoxycytidine 5'-triphosphate + 200U/ml Klenow fragment,
- c) 5μM deoxyguanosine 5'-triphosphate + 200U/ml Klenow fragment,
- d) 5μM deoxythymidine 5'-triphosphate + 200U/ml Klenow fragment,
- 30 To each mix 100μCi/ml of the corresponding ³²P labelled deoxynucleotide triphosphate was added (Amersham PB204, 205, 206 and 207).

The mixtures a-d were added singly in the sequence in which they appeared in the template strand
35 as follows:-

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Single nucleotide additions

1. The silver slide was placed on the biosensor hemicylinder and its position marked. The flow cell was placed on top of the slide.
- 5 2. 3ml of 10mM phosphate buffer pH 7.4 was flowed over the silver slide.
3. 1ml of 10mM phosphate buffer pH 7.4 containing 10mm $MgCl_2$ and 50mm NaCl was flowed over the silver slide.
4. 100 μ l of the nucleotide / enzyme mix was injected
- 10 and left on the silver slide for 5 minutes at room temperature.
5. The silver slide was washed with 5ml of 10mM phosphate buffer pH 7.4 containing 10mm $MgCl_2$ and 50mm NaCl + 0.005% Tween 20.
- 15 6. The silver slide was removed and blotted to remove any surface fluid then counted on the tritium channel of a scintillation counter.

Incorporation of the deoxynucleotide was determined from the increase in counts on the silver slides and calculated from the specific activity of the nucleotide/polymerase mixture used at that step.

The results are shown in Table 1.

7. The silver slide and flow cell were replaced on the biosensor in the same position and steps 3-6 were
- 25 repeated with the next nucleotide/polymerase mixture until the predetermined nucleotide addition sequence was completed.

Control silver slides were subjected to the same nucleotide addition procedure.

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Results

5 Correct Sequence Single Nucleotide Addition to Silver
Slide Immobilised DNA

10	Addition Nos.	Nucleotide Added	Radioactivity (counts per minute)	Moles nucleotide added /slide
15	1.	T	127	7.5×10^{-15}
20	2.	G	253	1.3×10^{-14}
25	3.	T	651	2.3×10^{-14}
30	4.	G	702	5.3×10^{-15}
35	5.	A	925	1.8×10^{-14}

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Conclusion

The addition of successive single nucleotides by the Klenow fragment of DNA polymerase I to this primer template hybrid immobilised at the silver 5 surface can be observed with radioactively labelled nucleotides.

In the absence of the primer template hybrid no successive increase in nucleotide addition is observed.

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CLAIMS

- 5 1. A method of sequencing a single-stranded nucleic acid chain, which method comprises:-
 - a) providing a template-primer complex comprising the single-stranded chain (the template) and at its 3'-end a double stranded chain (comprising the primer), the complex being attached at one end to a solid surface,
 - b) presenting a single nucleotide or nucleotide analogue to the complex in the presence of a polymerase under conditions to cause an extension of the primer (a polymerisation event) by addition of the nucleotide (or analogue) to the 3'-end of the primer if the nucleotide (or analogue) is complementary to and can hybridize to the next free nucleotide at the 5'-end of the template, and
 - c) repeating step b) successively using different nucleotides or nucleotide analogues,
 - d) the method being characterized by detecting a change in the template-extended primer complex resulting from each polymerisation event that occurs during performance of steps b) and c).
- 25 2. A method as claimed in claim 1, characterised by detecting, directly and by spectroscopic means, each polymerisation event that occurs during performance of steps b) and c).
- 30 3. A method as claimed in claim 2, wherein each polymerisation event is detected by evanescent wave spectroscopy.
- 35 4. A method as claimed in claim 2, wherein each polymerisation event is detected by attenuated total reflection spectroscopy.
5. A method as claimed in claim 2, wherein fluorescent nucleotide analogues are used in steps b)

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and c) and each polymerisation event is detected by total internal reflectance fluorescence spectroscopy.

6. A method as claimed in claim 2, wherein each polymerisation event is detected by surface plasmon resonance spectroscopy.

7. A method as claimed in claim 6, wherein high refractive index nucleotide analogues are used in steps b) and c).

8. A method as claimed in claim 2, wherein 10 fluorescent nucleotide analogues are used in steps b) and c) and each polymerisation event is detected by fluorescence spectroscopy.

9. A method as claimed in claim 2, wherein each 15 polymerisation event is detected by absorption spectroscopy.

10. A method as claimed in any one of claims 1 to 9, wherein the single-stranded nucleic acid chain is DNA.

11. A method as claimed in any one of claims 1 to 20, wherein a continuous flow of pulses of deoxynucleotides (dATP, dCTP, dGTP, dTTP) or ribonucleotides (ATP, CTP, GTP, UTP) or analogues of these nucleotides, each separated by a wash pulse, is passed over the complex attached to the solid surface.

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DNA SEQUENCING BY SPRS DETECTION OF TEMPLATE COPY GROWTH:
EXPERIMENTAL ARRANGEMENT

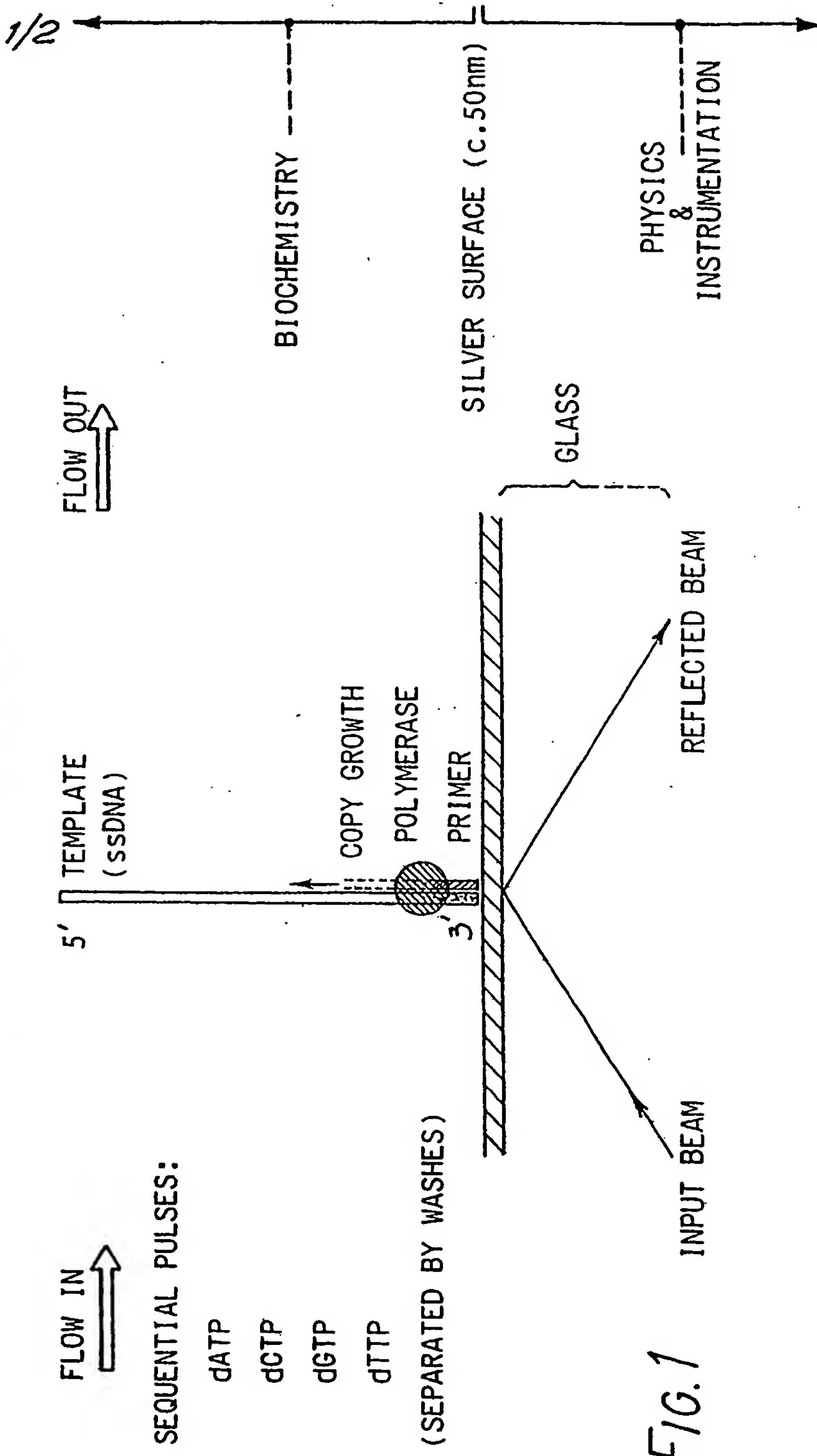
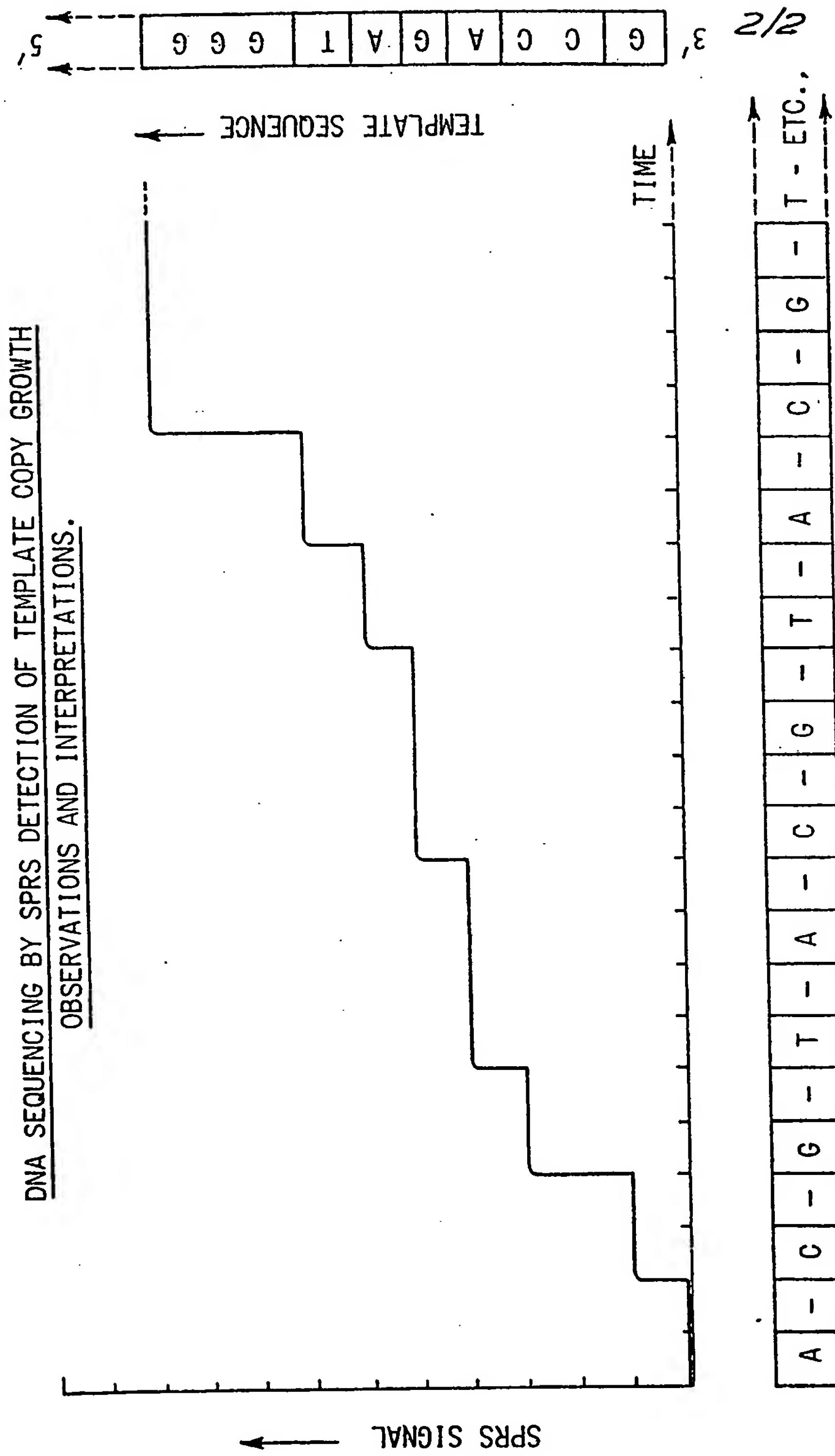


FIG. 1



dNTP IN FLOW MEDIUM (-REPRESENTS WASH)

FIG. 2

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